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TRANSACTIONS
OF THE
ILLUMINATING ENGINEERING SOCIETY

FOUNDED IN LONDON 1909

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VOLUME 21
No. 9 — 1956

32 VICTORIA ST
LONDON, SW1

Annual Subscription to Non-Members - £2.2.0
Price per Number to Non-Members - 5s. 0d.

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Relative Brightness of Coloured Light Sources

By H. M. FERGUSON, A.M.I.E.E. *(Member)*,
and W. R. STEVENS, B.Sc., M.I.E.E. *(Fellow)*

Summary

Experiments in the laboratory to compare the apparent brightness of mercury and sodium light sources of high luminance show that most observers do not judge brightness on the ordinary photometric scale. In some circumstances the mercury luminance must be reduced to one third that of the sodium before observers, on balance, judge them to be equally bright.

Similar, but less marked, results were found in a formal street lighting test, a mercury installation being judged more glaring than a sodium. This, however, did not produce a marked preference for the sodium installation.

The commonly expressed preference for sodium street lighting may be partly explained by the reduced glare from sodium sources as compared with mercury but, it appears, is largely due to the characteristics of lanterns and installations now in use.

It appears that a majority of road users prefer sodium street lighting to high-pressure mercury, but it is not easy to decide why such a preference is expressed. Some observers state that there is less dazzle with sodium street lighting, others find it gives better visibility, fewer shadows, less eye-strain, and so on. Judgment of the relative merits of various light sources in the street is very difficult, because in no two installations are the conditions sufficiently similar to make the comparison easy or even fair. In particular, most of the sodium street lighting in this country has been installed in the last few years; the lantern spacing is usually close, and the installations are well planned, whereas many H.P.M.V. installations are pre-war and less generously planned than we now regard as satisfactory.

Various investigations have been made on the relative merits of different light sources for street lighting and for vehicle lighting, but these investigations do not give a clear indication that any one source is better than others. Hopkinson[1], for example, in some model experiments from which was evolved a formula for evaluating discomfort glare, found no significant difference between different coloured sources: experiments on the penetration of fog and mist, particularly directed towards determining whether yellow-coloured headlamps were valuable[2], showed no clear advantage for them.

Nevertheless, so many road users appear to prefer sodium street lighting that it was thought worth examining the matter once again to see if any basis for such a preference could be found. The experiments which were made and the results which they give are described in this paper.

(1) Experiments in the Laboratory

(1.1) Comparison of "flash patterns"

It was thought that a possible difference between mercury and sodium street lighting lanterns might lie in the different formation and brightness of the flashed areas of the lanterns. The H.P.M.V. lamp has a much higher luminance than the sodium lamp, and the maximum intensity in the distribution is, therefore, obtained from a relatively small area of high luminance, even though in many designs measures are taken to break up the "flash pattern" into a mosaic in order to reduce the apparent brightness and to produce a large apparent flashed area. A simple experiment was,

The authors are with the Research Laboratories of The General Electric Co., Ltd., Wembley, England. The manuscript of this paper was first received on February 9, 1956, and in final form on March 5, 1956. The paper was presented at the Society's Summer Meeting at Harrogate on May 11, 1956.

therefore, set up in which two similar refractor lanterns of the type shown in Fig. 1 were equipped respectively with an ordinary vertical-burning H.P.M.V. lamp and a similar lamp enclosed in a lightly frosted glass cylinder. In this way it was possible to arrange the two lanterns to have the same maximum intensity, namely 2,000 candelas, and the same apparent flashed area, but with considerably different flash patterns (Fig. 2). The two lanterns were placed side by side and viewed from 80 ft. by a number of observers who were asked to say whether they found one more glaring than the other. The collective opinions of the observers showed no preference. There was a spread in the results as some thought the one more glaring than the other, but the number of observers favouring one source balanced very nearly the other.

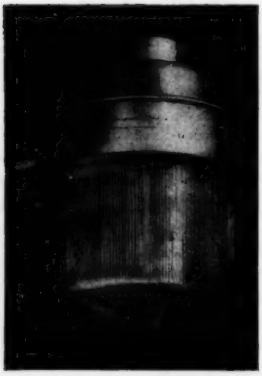
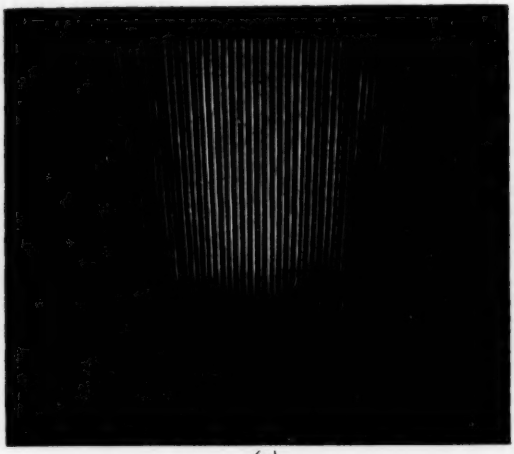
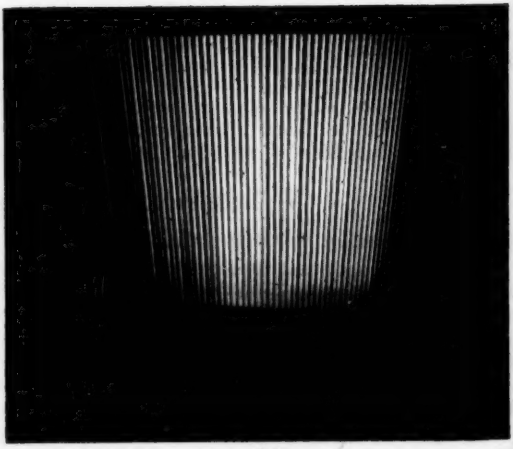


Fig. 1. Refractor-type street lighting lantern.



(a)



(b)

Fig. 2. Comparison of "Flash patterns": (a) with standard H.P.M.V. lamp, (b) with H.P.M.V. lamp in diffusing cylinder.

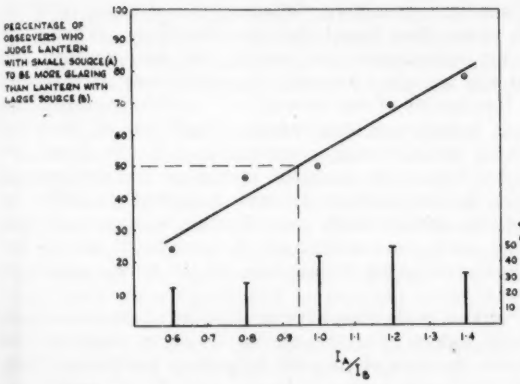


Fig. 3. Observer bias factor for comparison of "flash patterns" shown in Fig. 2.

(1.2) Test procedure

The method of appraising observer preference was as follows:—Each observer was asked to state which source appeared the more dazzling and each observer was allocated one mark. If he thought source A more dazzling than source B, his mark was allocated to A. If he thought source B the more dazzling, his mark was allocated to B. If he could observe no difference between the two, half a mark was allocated to each. The total of marks for each source was expressed as a percentage of the total available marks and, in the curve of Fig. 3, is plotted vertically to show the percentage of observers finding source A more dazzling than source B. For convenience this percentage is sometimes referred to as "observer bias factor." Plotted horizontally is the ratio of the intensity of the lantern with the small source (I_A) to that with the large source (I_B). By keeping I_B constant at 2,000 candelas and varying I_A it was possible to determine the observer bias factor at a series of ratios of I_A/I_B At each ratio there were at least 12 observers, the mean results being shown by the points on the graph.

For an observer bias factor of 50 per cent.—that is, when opinions are equally divided as to the more dazzling source—the ratio I_A/I_B is 0.95. Within the accuracy of the experiment, this ratio may be taken as 1. It follows, therefore, that when the intensities and apparent flashed areas are equal, the dazzle appears equal irrespective of the flash pattern within the apparent flashed area. The flash patterns used, though greatly different, were similar to those encountered in practical street lighting lanterns

The percentage of observers who were undecided is also shown in Fig. 3. A record of these undecided observations is useful, because it gives some indication of the extent of the difference in dazzle which was found: where the one source is considerably more dazzling than the other, the number of undecided observations is small; where the difference between sources is small, the number of undecided observations is large.

(1.3) Comparison of colour

It was now decided to investigate the apparent brightnesses of sources of equal area giving the same intensity, but provided by different types of lamps[3]. Two sources of uniform luminance were set up side by side, each was approximately 8½ in. wide by 4½ in. high. The sources were similar in all respects except that one employed an H.P.M.V. lamp and the other a sodium lamp. The luminances were carefully measured on the ordinary photopic scale to ensure that they were equal; the maximum value obtainable was of the order of 50 cd/in^2. The experimental arrangements by

which this was achieved are shown in Appendix I. Observers at a distance of 80 ft. were now asked to state which source they found the more dazzling. They were asked to give their reactions (a) immediately on viewing the two sources and (b) after an interval of at least one minute. A series of observations of this kind was made in which the relative luminances of the mercury and sodium sources could be compared. Thus, for example, a sodium source having a luminance of 50 cd/in^2 could be compared with a mercury source having a luminance of 40, 30, 20 cd/in^2, and so on. The sodium source was kept at its maximum luminance and the mercury source luminance was changed by the interposition of either a neutral glass filter or wire mesh screens. It was found that similar results were obtained whichever of these luminance reduction devices was used, thus supporting the results of the earlier experiment which showed that the nature of the flashed area did not have a significant effect upon the observers.

In the curves of Fig. 4 the vertical scale shows the percentage of observers finding mercury more dazzling than sodium, i.e. the mercury/sodium observer bias factor. The horizontal scale shows the ratio of mercury to sodium intensities. With both the neutral glass and the wire mesh screen a heavy majority of marks was accorded to the mercury source as the more dazzling when the intensities were equal: in fact, over 90 per cent. judged the mercury to be the more dazzling.

As the intensity of the mercury source was reduced, the intensity of the sodium

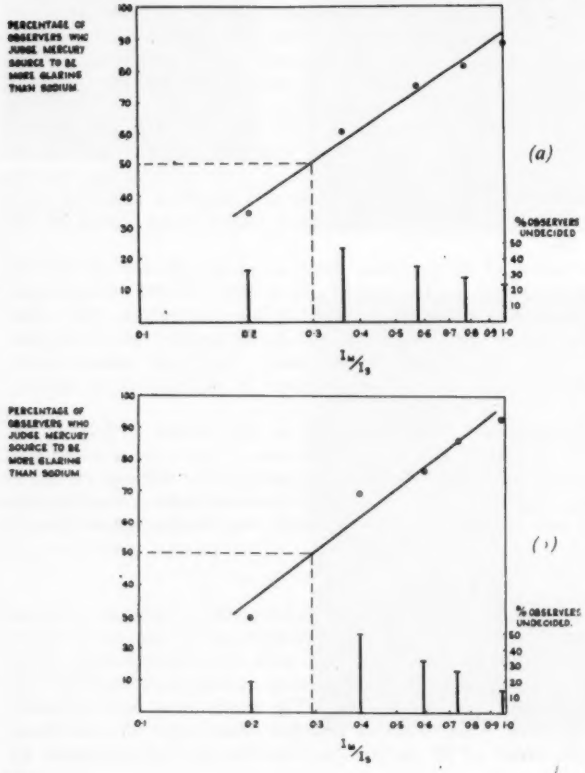

PERCENTAGE OF OBSERVERS WHO JUDGE MERCURY SOURCE TO BE MORE GLARING THAN SODIUM
(a)
% OBSERVERS UNDECIDED
I_M/I_S
PERCENTAGE OF OBSERVERS WHO JUDGE MERCURY SOURCE TO BE MORE GLARING THAN SODIUM
(b)
% OBSERVERS UNDECIDED
I_M/I_S

Fig. 4. Observer bias factor for comparison of mercury and sodium sources: (a) with neutral glass filter (b) with wire mesh filter.

source remaining constant, the number of observers finding the mercury source more dazzling decreased. At the same time, as would be expected, the number of observers unable to say which source was the more dazzling increased until the general opinion began to swing in the direction of finding the sodium source more dazzling than the mercury one.

Considering the appraisal after one minute, it appears that the luminance (and therefore the intensity of the mercury source) must be reduced to 0.3 of that of a sodium source before the observer judgment is equally balanced between the two.

The initial reaction of the observers, which is shown in Fig. 5, was to state the mercury as even more dazzling, and it was found through all the experiments that the initial reaction to the comparison was more violent than that after one minute, and the slope of the curve was usually steeper. However, although this initial reaction may have some significance in practical circumstances (see Section 3), the observations recorded for these conditions were generally more erratic and the results are not included in the results given later in this paper. All subsequent arguments apply to observations made after an adapting period.

(1.4) The effect of background brightness

The experiment was now repeated with a series of background luminances. From the results, the observer bias factor was determined for the condition when the luminance of sodium and mercury sources was equal. The results are shown in Fig. 6. The

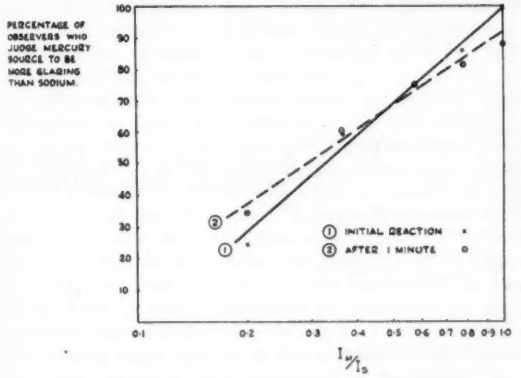


Fig. 5. Observer bias factor for comparison of mercury and sodium sources showing reaction initially and after one minute.

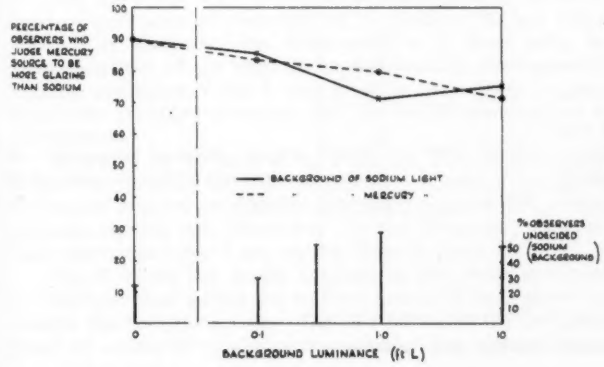


Fig. 6. Observer bias factor for comparison of mercury and sodium sources showing effect of background.

background luminance plotted horizontally is shown on a logarithmic scale, and the curve is broken, therefore, between 0 and 0.1 ft.-lambert. There is no significant difference between the results obtained with backgrounds illuminated with mercury or sodium light. The results at zero background luminance agree with those in Fig. 5, and, in general, the percentage of observers finding mercury more dazzling than sodium decreases as the background luminance is increased. But the bias factor never falls to the 50 per cent. value, which would be obtained if, on average, the observers found the two sources equally dazzling. It will be observed, too, that in the region of background luminance around 0.1 ft.-lambert, which is commonly encountered in street lighting installations, the observer bias factor was found to be over 80 per cent.

(1.5) Comparison with tungsten sources

A comparison was now made between mercury and tungsten and between sodium and tungsten light sources, and each of these comparisons was made for a range of background luminances. The two sets of results are given in Figs. 7 and 8. When mercury and tungsten were compared on a dark background, it was found by an observer bias factor of 60 per cent. that the mercury source was the more dazzling. In order to secure 50 per cent. for each source it was necessary to reduce the mercury intensity to 0.8 of the tungsten intensity. Once again the effect of background luminance was relatively small. In comparing tungsten and sodium sources it was found that when the intensities were equal, 85 per cent. of the marks claimed that the

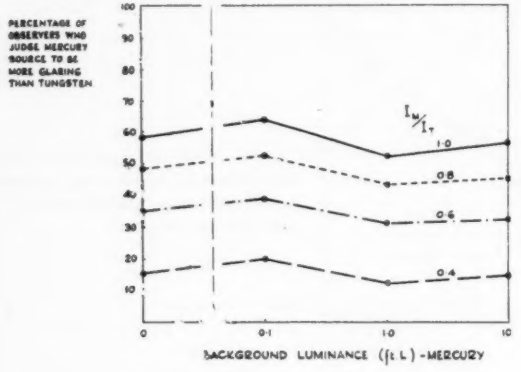


Fig. 7. Observer bias factor for comparison of mercury and tungsten sources.

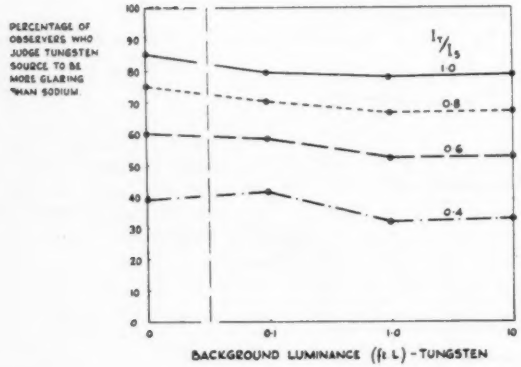


Fig. 8. Observer bias factor for comparison of tungsten and sodium sources.

tungsten source was the more glaring. An equality of marks was obtained when the ratio of tungsten intensity to sodium intensity was 0.5.

It is interesting to deduce from these results the effect which would be expected from a direct comparison between mercury and sodium, and to compare it with the direct comparison as measured. If we assume a sodium source whose intensity is 10 units (on any arbitrary scale) then the tungsten source will appear equally bright if its intensity is 5 units, a mercury source should appear equally bright if it has an intensity of 0.8 × 5, namely 4, as compared with the original equivalent sodium source of 10 units. The ratio for mercury : sodium is thus 0.4. In the direct experiment a ratio of 0.3 was established. These two values are in good agreement for an experiment of this type.

(1.6) Effect of ultra-violet radiation

At this stage a check was made to confirm that there was no effect due to ultra-violet radiation from the mercury source, although the previous comparison using tungsten light suggests that such an effect is unlikely. In fact, no difference could be discovered when the mercury discharge source was covered with an ultra-violet absorbing filter.

(1.7) Observations over a greater range of luminance

The observations made so far were concerned only with high luminance levels, such as are obtained from street lighting lanterns when viewed in the direction of maximum intensity. A further series of experiments was made, therefore, to cover a considerably greater range extending into the low luminance regions where the Purkinje effect might be observed.

The experimental technique was modified in several ways, the arrangement being described in detail in Appendix 2. In this series of tests the observers were always asked to compare the apparent brightnesses of sources set up to equal measured luminances. The observer viewed monocularly from 12 in. a bipartite circular field divided vertically. Care was taken to ensure that the luminance was uniform from each half of the field and by an arrangement of neutral filters, etc., the luminance of each side could be varied over a range of 10,000,000 to 1 from about 50 cd/in^2 down to 4.5 × 10^{-6} cd/in^2. Observers were asked to state which half of the field appeared the brighter, and by varying the luminance in steps of about 10 : 1, the sources being kept at equal luminance as measured on the photopic scale, a new series of observer bias factors was obtained. Exact equality of luminance could be achieved by making slight changes in the current through the mercury lamp.

The apparatus was calibrated in two ways : (a) by direct photometric measurement of luminance of each half of the field at the low luminance end of the range; and (b) by measuring the illumination at a fixed point in front of the eyepiece from each half of the field at the high end of the luminance range. At one intermediate luminance value it was possible to measure by both methods, and a good check was obtained to ensure that the values were correct all through the range of luminance.

It should be noted that the field size used in this experiment was considerably larger than that for the work described previously. In the direct comparison of high luminance sources, each source subtended about a half a degree at the observer's eye, and the viewing was binocular. In the monocular experiment, the whole circular field subtended some 4 deg. at the observer's eye.

Fig. 9 shows the results obtained in this series of experiments. The percentage of observers who judged the mercury source to be brighter than the sodium is plotted against the field luminance. The two halves of the field were always adjusted to be equal as measured on the photopic scale : the observations were all made after one

minute, or more, adaptation. Each point shown on the curve represents at least 12 observations. All observations were made against a dark background.

At the highest level explored, which was 22,600 ft.-lamberts (50 cd/in^2), the observer bias factor recorded in favour of mercury appearing the brighter source was about 80 per cent. This ratio is a little lower than that recorded in the earlier experiment with the small sources. As the field luminance is decreased, the bias factor diminishes, reaching 50 per cent. at a luminance (the two sources being of equal luminance) a little below 100 ft.-lamberts. This is in the region in which one would expect to get results directly in accordance with the ordinary photopic photometric scale, that is, the scale based on the accepted curve of relative luminous efficiency of the eye under photopic conditions. Therefore, at luminances of the order of 100 ft.-lamberts down to 0.01 ft.-lambert it was expected that observer bias would be equally balanced between mercury and sodium sources. In fact, as the curve shows, over a large range of luminances, namely, between about 100 and 0.01 ft.-lambert, there was a tendency to find that the sodium source appeared brighter. Below this value of luminance the expected Purkinje shift was observed, so that once again the mercury source appeared brighter to the majority of observers.

The region in which the curve drops below 50 per cent., therefore, needs some special comment, and one explanation for this result may be as follows. If we refer once again to Fig. 4 (a) we find that at high luminance levels (around 20,000 ft.-lamberts), in order to shift the observer bias factor from 50 per cent. to 25 per cent., the ratio

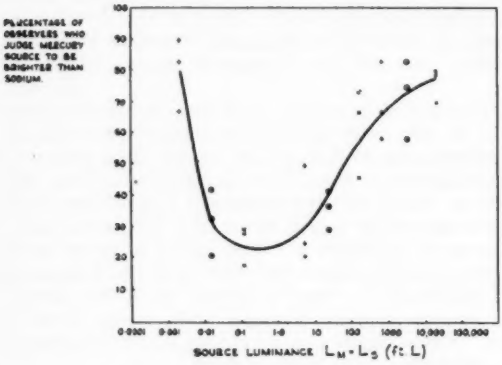


Fig. 9. Observer bias factor for comparison of mercury and sodium sources of equal luminance.

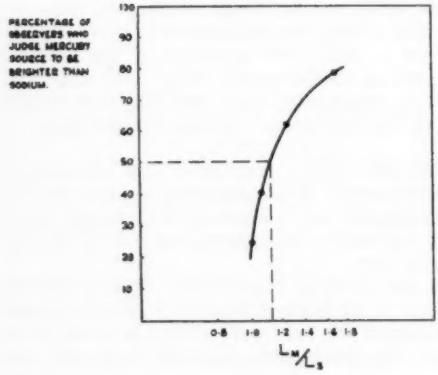


Fig. 10. Observer bias factor for comparison of mercury and sodium sources at a luminance of about 0.1. ft. L.

I_M/I_S has to shift from about 0.3 to rather below 0.2. This change in observer preference is associated, therefore, with a 50 per cent. change in intensity ratio and small differences in intensity, therefore, cause relatively small changes in observer bias at high levels. In order to determine the rate of change of observer bias factor with luminance ratio at a level of about 0.1 ft.-lambert, a series of measurements was made on the monocular viewing apparatus in which the sodium source was maintained at a luminance of 0.134 ft.-lambert and the mercury source was varied in luminance. The results of these observations are shown in Fig. 10, in which it will be seen that the curve is very steep. A change of less than 15 per cent. in the ratio of mercury to sodium luminance will produce a change in observer bias factor from 25 per cent. to 50 per cent. It is evident, therefore, that this region of the curve is very critical, and that small errors in photometry could account for the fact that the curve dips below the 50 per cent. which was expected.

On the other hand, some observers have suggested that the photopic relative luminous efficiency curve, as agreed internationally, may be in error in such a way as to make a monochromatic yellow source appear brighter than a monochromatic green source of equal luminance: these suggestions were based on measurements made at levels around 3 ft.-lamberts[4]. The extent of this effect is not generally agreed, but it could explain why the curve of Fig. 10 falls in part below 50 per cent. observer bias factor.

(1.8) Conclusion from laboratory experiments

There seems no doubt from these experiments that at high levels of luminance there is a marked tendency for observers to find that sodium radiation appears considerably less bright than either mercury or tungsten filament, although on the ordinary photopic scale they are measured as being equal. The results of the monocular judgment experiments at levels between 0.001 and 10 ft.-lamberts are in general agreement with those which would be expected, but at high levels the eye appears to become "mercury-sensitive." At luminances of the order of 50 cd/in^2 the sensitivity of the eye to light of different wavelengths is such that the relative luminous efficiency curve no longer holds. The effect is as if the curve had shifted towards the short wavelength end of the spectrum in a way similar to the shift already well established for scotopic vision, or as if some distortion of the curve had raised the blue end at the expense of the yellow.

The method of test does not give a measure of the amount of difference between the sources, except in so far as this can be estimated from the number of observers who are uncertain about which source appears the brighter. Nevertheless, a sufficient number of observations was taken to establish that the results given are substantially correct for the experiment in the form in which it was made. The results of tests on a 4-deg. bipartite field are not markedly different from those on the ½-deg. sources.

(2) Experiments in the Street

(2.1) Design of experiment

It would be unwise to conclude from the laboratory experiments that reduced glare is the cause of the preference for sodium street lighting, because there are many other factors which enter into street lighting installations. A series of experiments was, therefore, made to compare mercury and sodium street lighting installations designed to be similar in all respects except colour.

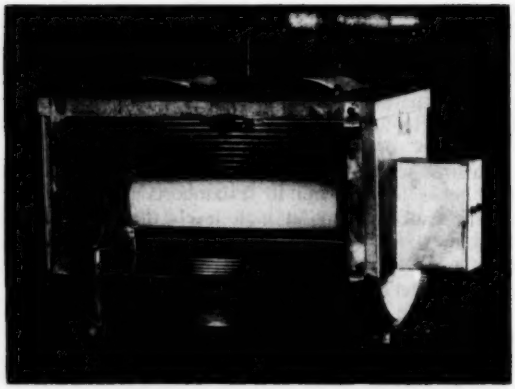
Eight lanterns were constructed. Four of these used 140-watt integral sodium lamps with the ends masked: and the other four 400-watt H.P.M.V. lamps with sprayed outer jackets and the ends similarly masked. Thus the sources all had substantially the same luminance and physical dimensions.

The lanterns are shown in Fig. 11 (a) and (b). The primary optical control was

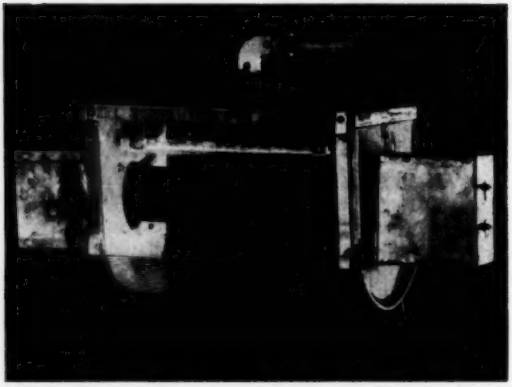
obtained with two side refractors and a fluted bottom glass, the design being the same for both mercury and sodium lanterns. Some slight internal modifications were necessary to obtain similar "flash" patterns and light distributions. The appearance of the lanterns seen in the direction of maximum intensity was as shown in Fig 12, and the light distribution was as in Fig. 13. The maximum intensity was 1,500 candelas, giving an average "flash" luminance of 22 cd/in^2 and the light emitted in the lower hemisphere was 3,600 lumens.

The lanterns were erected on a straight level road to form a continuous staggered installation with a spacing of 100 ft. and a mounting height of 15 ft. The mercury lanterns were at one end of the installation, and the sodium lanterns at the other, so that an observer standing in the middle could view them consecutively. The road was carefully chosen so that from the middle the views in each direction were as alike as possible. In particular, the buildings on either side and the distant views were similar in both directions.

Although the experiments were made in a side road for convenience, with mounting height and spacing appropriate to a Group B installation, the illumination levels obtained were at the low end of the range for traffic route lighting. The light output



(a)



(b)

Fig. 11. Experimental lanterns (refractor panels removed); (a) mercury, (b) sodium.

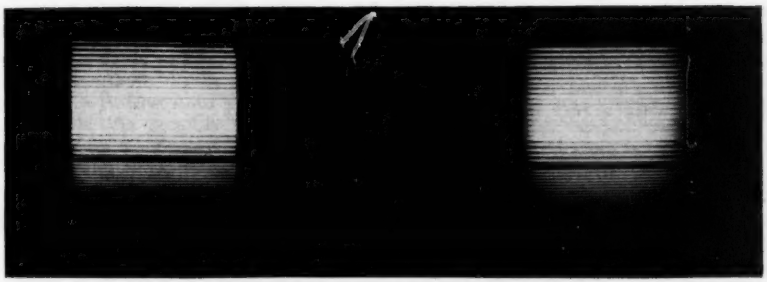


Fig. 12. "Flash patterns" from experimental lanterns (sodium on the left).

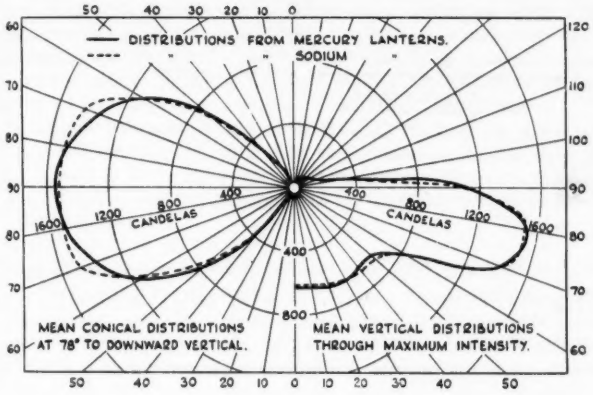

DISTRIBUTIONS FROM MERCURY LANTERNS.
" " SODIUM "
CANDELAS
MEAN CONICAL DISTRIBUTIONS AT 78° TO DOWNWARD VERTICAL.
MEAN VERTICAL DISTRIBUTIONS THROUGH MAXIMUM INTENSITY.

Fig. 13. Light distributions from experimental mercury and sodium lanterns.

Fig. 14. Part of experimental installation by day.

in the lower hemisphere could be varied between about 2,200 and 4,500 lumens per 100 ft. linear. The road width was 24 ft., and the pavements each 6 ft., and the distance between building lines was 86 ft. The road surface was gravel on pitch on a concrete base. It had been badly broken so that portions of all three materials were visible, producing a very patchy appearance (Fig. 14).

(2.2) Experimental procedure

For each experiment the lanterns were erected in the street at the correct spacing and mounting height, and the lanterns levelled. The electrical circuits were so arranged that the light output of the sodium lanterns was kept constant and that of the mercury lanterns could be varied by adjusting the applied voltage, over a range of 0.6 to 1.25 times that of the sodium lanterns.

The observers, of whom there were never fewer than 15, were each given the following questionnaire, which they were asked to complete whilst observing from the junction of the two installations:—

TEST NO.....

NAME .....

STREET TESTS TO COMPARE MERCURY AND SODIUM LIGHTING

QUESTIONNAIRE

Write "M" for mercury or "S" for sodium in column I below. If you have strong feelings in the matter use column II. If you are undecided put a dash—in column I.

	I.	II.
1. Which installation do you prefer ?		
2. Looking at a distant point on the road, which installation appears more glaring ?		
3. Looking at the lanterns, which appear brighter ?		
4. Which installation gives the brighter road surface ?		
5. Which installation gives the better uniformity of road brightness ?		
6. Which installation gives the better seeing conditions ?		
7. Which installation do you prefer for colour ?		
8. Which installation, if any, appears more misty or hazy ?		

Do you drive ?.....

Have you any particular comments to make ?.....

The mercury installation was varied in four steps over its range, giving four

ratios of mercury to sodium intensity (or light output) I_M/I_S. These different ratios were presented in random order, unknown to the observers, some being repeated. A questionnaire was answered by each observer for each ratio.

Such a series of tests took about one hour. The observations were now interrupted for a further hour during which time the installation was reversed, end-for-end, to eliminate the possible different effects of road surface, background, etc. The series of tests previously described was then repeated.

Two complete experiments were made on separate nights.

(2.3) Results

The results are shown in Figs. 15 (a) and (b). Observer bias factor is plotted vertically, and the ratio of H.P.M.V. to sodium intensity is plotted horizontally. The method of marking to obtain the observer bias factor was as in the laboratory experiments, one mark being awarded where the observer stated a preference, and a half mark to each installation where he was undecided. A preference expressed in column two was still recorded as a single mark, although these strongly expressed opinions sometimes gave an interesting qualitative impression of the difference between installations.

The mean results of the tests for the installation at each end of the road on each of the two nights are recorded. This gives four points at each chosen value of I_M/I_S. A smooth curve has been drawn through the average value for each set of four points. This method of plotting makes it possible to see the change in observer bias factor from end to end, and from night to night. However, the number of observations at each point is not sufficiently large (15-20 observers) to draw definite conclusions about individual points.

(2.4) Discussion of results from street tests

From Fig. 15 (a) when the lantern luminances were equal ($I_M/I_S = 1$) the percentage of observers finding that the mercury lantern appeared brighter than the sodium lantern was over 80 per cent. The point at which preference was equally divided between mercury and sodium sources was when the luminance of the mercury was about 0.6 that of the sodium. Thus the effect obtained in the street was similar to that observed in the laboratory, but to a less marked extent. In the laboratory, comparing mercury and sodium lanterns having equal luminance of 50 cd/in^2 on a dark background an observer bias factor of over 90 per cent. was found (Fig. 4). A rather lower observer bias factor would be expected for lower luminances (Fig. 9) seen against a lighter background (Fig. 6). Thus it is reasonable that the ratio of 0.6 for I_M/I_S to give an observer bias factor of 50 per cent. in the street is higher than the ratio of 0.3 obtained in the extreme conditions of the laboratory experiment (Fig. 4).

The results on glare (Fig. 15 (b)) are interestingly similar to those on lantern brightness. At the point $I_M/I_S = 1$, 80 per cent. of observers found the mercury installation more glaring than the sodium. In this test the observer was asked to look at a distant point on the road so that the furthest lantern was some 3 deg. from the line of sight and the nearest lantern at least 10 deg. from the line of sight. The sources were, therefore, viewed well away from the line of sight. De Boer and van Heenskerck Veekens[5] have also found recently that sodium light gives less discomfort glare in the street than mercury.

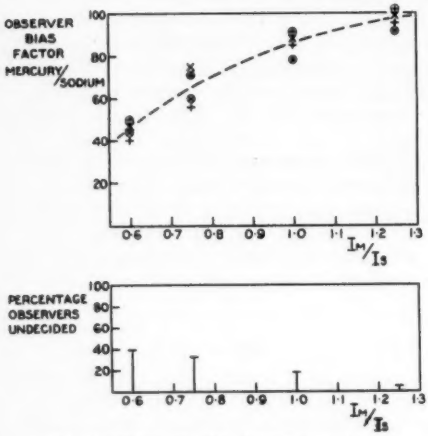
If glare were the dominant feature in street lighting we should expect the answer to the question: "Which installation do you prefer?" to be closely linked to the observations on lantern brightness and glare. However, one finds (Fig. 15 (c)) that when $I_M/I_S = 1$ there is only a small preference for the sodium installation, and mercury is increasingly favoured as the ratio I_M/I_S increases. The slope of the curve is quite small, the observer bias factor only changing by 30 per cent. for a

2 to 1 change in I_M/I_S ratio. The fact that the slope of this curve is positive shows that glare is not the over-riding factor.

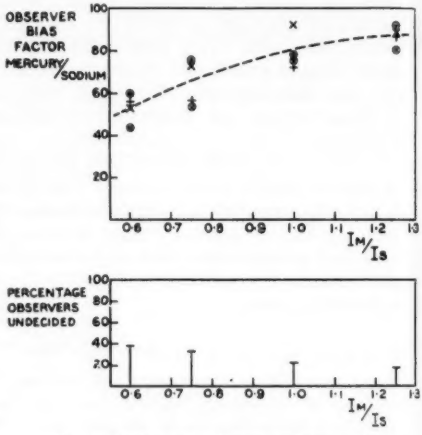
The curve giving answers to the question of "seeing conditions" (Fig. 15 (d)) is similar to that for "preference." This is, perhaps, not surprising since the preference for an installation is obviously closely linked with ability to see in it.

Fig. 15 (c) shows that when the luminance of the road surface was the same for the two installations* ($I_M/I_S = 1$) observers were equally divided in saying which appeared brighter. When the photometer says the surfaces are equally bright observers, on the average, agree. The curve has a steep slope, a 2 to 1 change in I_M/I_S ratio giving a 60 per cent. increase in observer bias factor: evidently observers

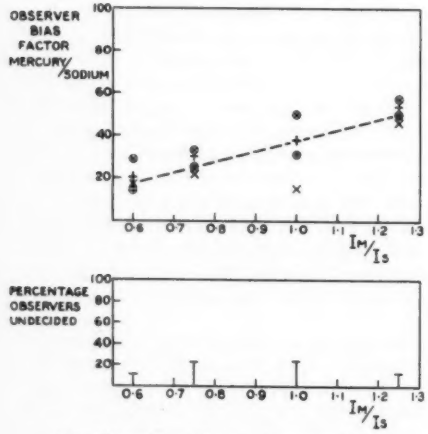
* This assumes that the reflection factor of the road surface is the same for the two sources.



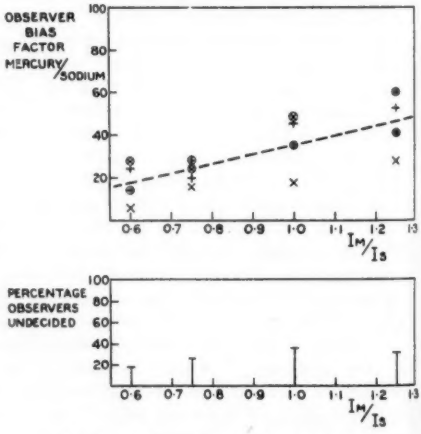
(a) Looking at the lanterns, which appear brighter?



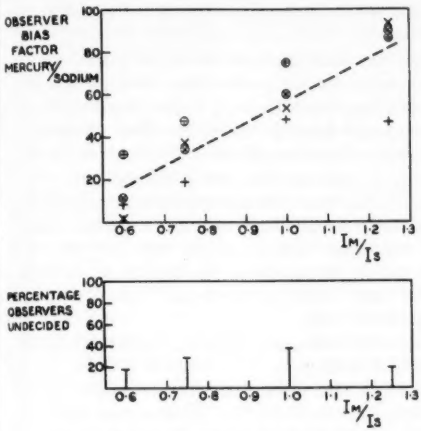
(b) Looking at a distant point on the road, which installation appears more glaring?



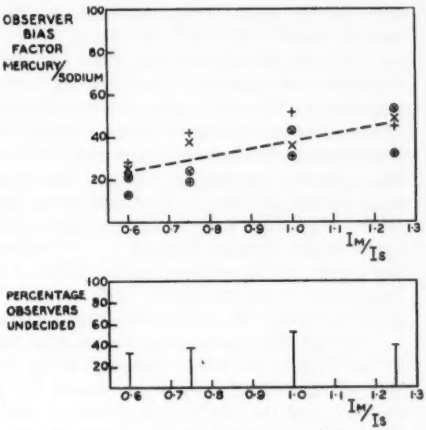
(c) Which installation do you prefer?



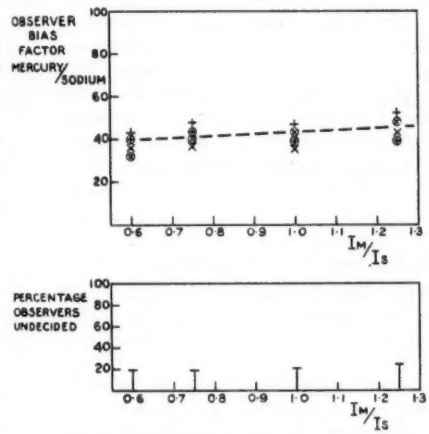
(d) Which installation gives the better seeing conditions?



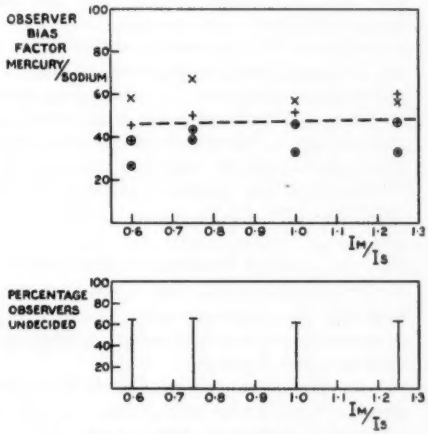
(e) Which installation gives the brighter road surface?



(f) Which installation gives the better uniformity of road brightness?



(g) Which installation do you prefer for colour?



(h) Which installation, if any, appears more misty or hazy?

× MERCURY AT NORTH END, 5.0 P.M.
⊗ MERCURY AT SOUTH END, 7.0 P.M.
} 7.12.1955, DAMP ROAD.

\+ MERCURY AT NORTH END, 7.0 P.M.
⊕ MERCURY AT SOUTH END, 5.0 P.M.
} 20.12.1955, WET ROAD.

Fig. 15. Observer bias factors for comparisons of experimental mercury and sodium street lighting installations (a to h).

are able to detect fairly small changes in road luminances under these conditions of test.

Fig. 15 (f) shows that observers judged the road surface to be a little more uniformly bright under sodium light than under mercury for the same level of lighting ($I_M/I_S=1$). Also, the curve has a small positive slope. The road surface was so uneven that perhaps the observations should be discounted but they seem too consistent to be ignored completely. It is possible that the diffuse reflection factor of the surface is greater to sodium than to mercury light so that the areas between the main bright patches appear somewhat brighter in the sodium installation. In this event, the sodium installation might appear more uniform than the mercury. The main bright patches formed by preferential reflection will be much less affected by the colour of the surface, particularly on the wet or damp road. Judgment of overall brightness would be mainly influenced by the main bright patches and would not be greatly affected by colour of road surface in these tests.

As the illumination on the road increases (with increasing mercury intensity) parts of the dark areas which were below the threshold brightness may become visible. This rate of growth of brightness would be greater in the dark areas than in the main patches, and the surface, therefore, would appear more uniform. This would explain the positive gradient of the curve in Fig. 15 (f) which, however, is small, so that changing the level of illumination does not appear to have a marked effect on judgment of road brightness uniformity.

Fig. 15 (g) and (h) show the results of observations on "colour" and "haziness." Both curves are substantially horizontal and show an equally divided preference for mercury and sodium which does not change significantly with luminance over the range examined. On average, therefore, neither of these factors seems to determine a preference for one source rather than another. The number of undecided answers on "colour" was small, showing that observers have a definite preference for one colour or another but the preferences are equally divided. The number of undecided answers on "haziness" was large, showing that there was little difference between the two sources. This was found also in a heavy fog when a mercury and sodium lantern were placed side by side and viewed from increasing range. There was no obvious difference in the amount of scattered light, or the point at which the lanterns disappeared from view.

(3) Reason for Preference for Sodium Street Lighting

The experiments in the street indicated some observer bias for the sodium installation, but the effect was much less than might be expected from the general comments of road users. In the authors' experience, over 80 per cent. of such comments favour sodium street lighting.

Of the several factors examined, "glare" (or "lantern brightness"), "seeing conditions" and "road uniformity," all favouring sodium, are the only ones showing a significant distinction between the sources. However, the overall preference for the sodium installation is small. Evidently the factors showing no observer preference, e.g., "road surface brightness," "colour," and "haziness" dilute strongly the effects of the other factors.

Glare is the only factor which shows a marked observer preference for sodium lighting, and is the only factor which shows an increasing preference for sodium as the ratio I_M/I_S rises. The curves for all the other factors are either flat, or show increasing favour for the mercury installation as the ratio I_M/I_S rises. Clearly these factors are largely swamping the deleterious effect of glare.

It still remains to explain why the ordinary road user expresses so strongly his preference for sodium street lighting.

Firstly, it must be remembered that in practice no two installations are alike:

indeed it has proved difficult to design installations sufficiently similar to make formal comparison possible. The value of casual observations is, therefore, doubtful.

Next, the bulk of sodium street lighting has been installed during the last ten years, whereas much mercury lighting is pre-war and of a considerably lower standard. An average spacing of 150 ft. is not uncommon in older mercury installations whereas modern sodium lanterns are some 120 ft. apart. To a large extent, therefore, comparisons are made between good sodium and mediocre mercury installations.

But even if we compare modern mercury and sodium installations we find interesting differences in lantern performance. Table 1 compares characteristics of three mercury and three sodium lanterns in common use for main road lighting.

Table 1

Lantern	Max. intensity (candelas)	Luminance (cd./in.²)	Light output in lower hemisphere (lumens)
250-watt HPMV	2300	50	5500
lamp light	2000	45	5000
output 8000 lms.	2500	110	4500
140-watt Sodium	2400	27	6500
lamp light	2000	21	6600
output 9000 lms.	2400	27	6200

On average the maximum intensity of the mercury and sodium lanterns is the same. The luminance in the direction of maximum intensity of the mercury lanterns is, however, some two to three times that of the sodium; and the sodium lanterns emit some 25 per cent. more light in the lower hemisphere. These differences will certainly make existing sodium installations appear more attractive than mercury. Indeed, a calculation of discomfort glare, based on the formulas devised by Hopkinson[1] suggests a difference in degree of glare approaching a "half-criterion" on his scale. For example, if the mercury installation is regarded as "just comfortable" the sodium will be nearly half-way to "satisfactory." The criteria used by Hopkinson were "just tolerable," "just comfortable," "satisfactory" and "just not perceptible" glare. The steps between these are large, and half a step is quite noticeable. In the street tests described in Section 2 of this paper the change in discomfort glare represented by the two extremes of mercury intensity ($I_M/I_S = 0.6$ to $I_M/I_S = 1.25$), represent only about one-quarter of the step between Hopkinson's criteria, and yet this was accompanied by a marked change of observer bias factor, from 55 per cent. to 85 per cent. in the appraisal of glare.

It is evident, therefore, that the differences between the mercury and sodium lanterns in current use are sufficient to explain a common preference for sodium lighting as being less glaring, even assuming that mercury and sodium sources of equally high luminance appear equally bright. But as shown previously in this paper, mercury sources tend to appear brighter than sodium for nominally equal luminance. This must tend to bias opinion even more in favour of sodium street lighting as being less dazzling.

The way in which observers react to the greater amount of light in typical sodium installations compared with mercury may also be deduced from the street test. When the two experimental installations were running at $I_M/I_S = 0.75$ the number of votes cast in favour of the sodium installation was 75 per cent. This marked preference

for sodium lighting was recorded in spite of the fact that the sodium lanterns had a higher intensity and luminance.

The dazzle effect is also probably enhanced by the fact that the mercury source appears particularly bright on initial exposure (see Fig. 5), and this effect may be significant to a driver passing from one installation to another.

(4) Conclusions

(1) Experiments in the laboratory on sources of $\frac{1}{2}$ deg. and 4 deg. subtense show that at high values of luminance the apparent brightness of mercury, sodium and tungsten sources cannot be assessed on the standard photopic photometric scale. The discrepancy can be great: for example, a sodium source of 50 cd/in^2 appears only as bright as a tungsten source of about 25 cd/in^2 or a mercury source of about 15 cd/in^2 seen against a black background. Increasing background luminance up to 10 ft.-lamberts tends to reduce the difference slightly.

(2) There is some evidence supporting the view that the standard photometric scale underestimates the apparent brightness of sodium sources in the luminance range 0.01 to 10 ft.-lamberts.

(3) Experiments in the street confirm that, when presented with two installations similar in all respects except the light sources, observers show a small preference for sodium street lighting over mercury.

(4) The preference expressed by road users making casual observations is much more strongly favourable to sodium street lighting than was obtained in the controlled experiment. This may be explained by the characteristics of lanterns in common use. In these, the light output in the lower hemisphere is some 25 per cent. less for mercury than for sodium lanterns, and the luminance is considerably greater in the direction of maximum intensity.

Acknowledgments

The authors wish to thank the Wembley Borough Council for permission to conduct experiments in the borough, and Mr. C. W. Steedman, A.M.I.C.E., M.I.Mun.E., M.T.P.I., M.R.San.I., Borough Engineer and Surveyor, and his staff, for their assistance; also the Eastern Electricity Board and Mr. G. F. N. Blaxall, Senior Engineering Assistant, Northmet Sub-Area.

The authors also wish to thank the many observers who attended in rain, frost and fog for their tolerance and fortitude.

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(1) R. G. Hopkinson, Trans. Illum. Eng. Soc. (London), **5**, 1 (1940).
(2) Dept. Scientific and Industrial Research. Illumination Research Technical Paper No. 20 (H.M. Stat. Office, 1937).
(3) H. M. Ferguson, J. Reeves, W. R. Stevens, G.E.C. Journal, **1**, 7 (1953).
(4) H. Buckley, Reports on Progress of Physics, **8**, 318 (1941) (Physical Society, London).
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Appendix I

Experimental Apparatus Used for Tests Described in (1.3) to (1.6)

The apparatus used to produce the two sources of high luminance is shown in Fig. 16. It consisted of two parabolic trough reflectors mounted side by side at a distance of 80 ft. from a binocular eyepiece. Each mirror was "flashed" by a lamp at the focus of the parabola and suitably screened so that, from the viewing position, a part

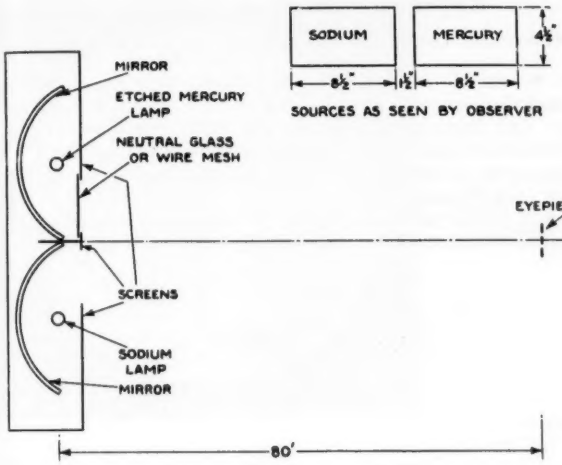

Fig. 16. Diagram of apparatus for comparing sources of high luminance.

of each reflector could be seen through a rectangular aperture measuring 8½ in. x 4½ in., the separation between the two being 1½ in. Great care was taken to ensure that the flash in each mirror was uniform, as seen by both eyes separately, and that there was no significant difference in intensity from each source in the direction of each eye.

The diagram shows the arrangement for comparing mercury and sodium sources. The mercury lamp was a 400-watt H.P.M.V. lamp with the outer jacket frosted in order to produce the required uniformity of source luminance, and the sodium lamp was a standard 45-watt SO/H so arranged that the centre of one limb was at the focus of the parabola. Reduction in mercury source luminance was achieved by placing a neutral filter or mechanical screen over the aperture and by adjusting the voltage on the lamp tc give the exact values required.

For the comparison of mercury and tungsten sources and sodium and tungsten sources the apparatus was modified slightly for convenience. The apertures now measured 8½ in. x 4 in. and the separation between them was increased to 7 in. A 500-watt line filament type lamp was used, with the filament at the focus of the reflector, and a sheet of frosted glass interposed between lamp and reflector to produce the required uniformity.

The apparatus was calibrated by measuring the illumination at the eyepiece from each source, using a visual illuminometer which itself was calibrated regularly throughout the tests. In this way the sources being compared could be set up to give any required intensity or luminance ratios without the necessity of knowing the transmission of the neutral glass or mechanical screens.

The observer was placed in a booth containing a small aperture for viewing the sources, so that the surround could be varied both in luminance and colour by illuminating the booth with the appropriate lamps.

Most of the observers taking part in the tests described in the paper were tested for colour vision by means of the Ishihara Charts. They all showed normal response. The average age of observers was about 30 years. Most of them were tested with the Snellen Chart, their average performance (with glasses where worn) being close to 6/6.

Appendix II

Experimental Apparatus Used for Test Described in (1.7)

The apparatus is shown in Fig. 17. Each half of the bipartite field was produced by viewing through a right-angled prism, the "flash" in a parabolic trough mirror from a mercury or sodium lamp. The front surfaces of the prisms were masked so that the field, as seen from the monocular eyepiece at a distance of 12 in., was circular with a diameter of $\frac{3}{4}$ in. The lamps were completely screened from the observer so that the field was seen against a dark background.

The luminance of each half of the field was reduced by interposing diffusing glass between the prism and the reflector and a neutral filter between the prism and the eye-

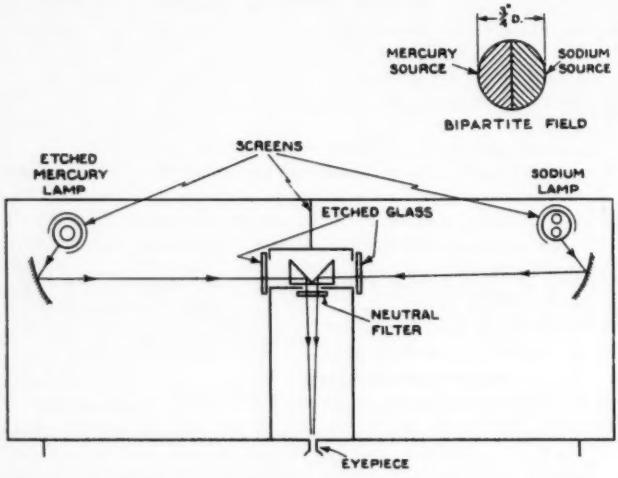

Fig. 17. Diagram of apparatus for comparing sources over a large range of luminance.

piece. For the lowest values of luminance the mirrors were replaced, firstly by diffuse white reflectors, and finally by matt black paper.

The bipartite field was photographed from the position of the eyepiece, using a high contrast plate, and suitably enlarged so that the uniformity of luminance could be checked and the areas of each half of the field could be measured accurately (Fig. 18). The areas were not exactly the same, the mercury field being some 4 per cent. larger than the sodium, but an allowance was made for this when calculating luminance values. The uniformity was very good.

The apparatus was calibrated as follows:—

(a) For high luminance levels—by measuring the illumination from each half of the field in turn at a point 4 ft. in front of the mask. From these illumination values the intensity, and therefore the luminance of each half of the field, could be calculated. There was at first some doubt about the position of the source in the optical train, a knowledge of which is required to calculate intensity values; but this was determined by a series of illumination measurements at various distances in front of the eyepiece. The source position was found to be precisely in the plane of the mask on the front surfaces of the prisms.

(b) For low luminance levels—by measuring the luminance of each half of the field directly with a visual photometer.

The following table gives the luminance levels for each series of tests shown in

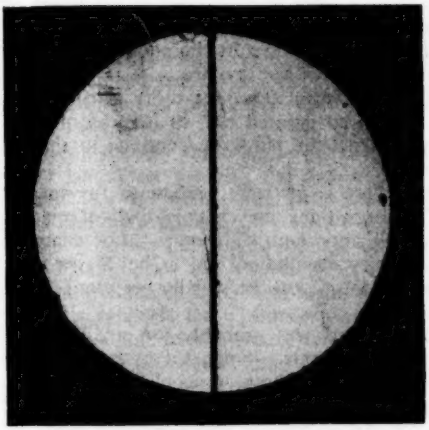

Fig. 18. Test for area and uniformity of luminance of bipartite field. Mercury source on left-hand side.

Fig. 9, the method of measurement, the level at which the measurements were made and also shows for which tests the neutral filter (NF) was used.

Test	1	2	3	4	5	6	7	8	9
Luminance ft.-L.	22,500	3,200	675	180	27	6.0	0.12	0.016	0.002
Method of measurement	←——Illumination Method——→					←Direct Luminance Method→			
Measured luminance ft.-L. approx.	1.0	0.1	0.02	1.0	0.1	0.02 6.0	12	1.6	0.2
Filter	–	–	–	NF	NF	NF	NF	NF	NF

For test 6, at a level of 6 ft.-L both methods of measurement were used and the luminance values agreed to within 5 per cent. For tests numbers 4-9 inclusive, the observations were made with the neutral filter in position. However, the apparatus was calibrated without the neutral filter in position (with the exception of test No. 6 when the direct luminance method was used) so that an accurate determination of the filter transmission for both mercury and sodium light was necessary to arrive at the field luminance. This transmission was determined with both visual and photo-electric photometers.

Discussion

MR. A. W. CHRISTIE: Mr. Ferguson and Mr. Stevens have set themselves a very difficult problem. Their title is simple enough, "Relative Brightness of Coloured Light Sources," but, in fact, they set out to discover the effect that the colour of light has on vision in lighted streets. Much careful work has gone into their experiments, and they are to be congratulated on getting so far with the problem.

In their laboratory studies, exciting discoveries were made of differences between the visual effects of mercury and sodium light. Since these differences apply mainly

at high luminances, we might expect their influence from glare to affect vision in lighted streets. However, in their carefully controlled street-lighting tests, the observers showed a much smaller preference for sodium than is shown by the public as a whole. The authors suggest that the marked public preference for sodium arises from differences in light distributions which make mercury installations the more glaring, even in the case of new installations. As Mr. Ferguson pointed out, so long as mercury lanterns are designed on this basis, we may expect the public to continue to show a preference for sodium.

Although the authors have shown that there is no large preference for sodium when similar installations are considered, I do not think they have entirely eliminated the possibility of there being smaller, but still important, differences. For example, Fig. 15c shows that the intensity in the mercury installation had to be 25 per cent. greater than that in the sodium installation for the two to be equally preferred. This result, if accurate, is probably important.

However, the number of observers taking part was probably too small for the numerical estimates to be considered entirely accurate. Since there appear to be considerable differences between observers, a sample of about 30 people may well have been biased one way or the other. Moreover, since there is a progressive yellowing of the lens of the eye with age, the preference for colours may be associated with age.

The authors appear to be concerned to demonstrate from their results that glare is not the dominant factor in street lighting. This is not really necessary : as the intensity of the lanterns in an installation is raised, discomfort glare increases, but so does revealing power, and the overall effect is usually considered beneficial. Thus, to replace 250-watt lamps with 400-watt lamps is thought to be an improvement. The positive slope of Fig. 15c, showing the preference for mercury to increase as the intensity of the mercury lighting was raised, while that of sodium stayed constant, is what we would expect.

Hopkinson's formula for discomfort glare suggests that the glare curve in Fig. 15b should be flatter, i.e., rise more slowly, than the lantern brightness curve, which is in Fig. 15a. In fact, the two curves are very closely similar. I wonder if some of the observers failed to look at the road as requested, but allowed their attention to stray to the actual lanterns in the installation, so that what they recorded as their assessment of glare was merely a duplication of their assessment of lantern brightness.

With regard to the greater uniformity of the road brightness with sodium, the authors suggest that the surface may have had a higher diffuse reflection factor for sodium than for mercury. We tried, at the Road Research Laboratory, to check this with a similar surface, and there seemed to be some such effect. If so, there may be some virtue in choosing lamps according to surfaces and vice versa. We also tried to find out, analysing what data we had on accident statistics, whether the proportion of accidents which occur at night is different in new installations of mercury and sodium. There was no significant difference, and it was clear that a vastly greater amount of data than was available would be required to demonstrate any difference.

Much of the paper I have not dealt with ; I am sure there are many other speakers who will make up for that. In conclusion, may I express the hope that the authors will be able to extend their valuable work in order to settle more definitely the magnitude of any differences that may exist between vision in lighted streets with mercury and sodium installations.

MR. H. R. RUFF : The paper has given a good picture of the careful work which is being undertaken to sort out a problem, which started with us in the thirties, when sodium and mercury lamps came into being.

We were then rather concerned with whether, if we applied light of such different colours as mercury and sodium to the streets, we should get visibility on the roads

corresponding to the light intensities we were putting on them. We found results closely in agreement with illumination values, although it is quite possible that some of that agreement was due to differences cancelling themselves out.

In practice visibility on the roadway seems to be proportional to the lumens per 100 ft. linear in the lower hemisphere from lanterns with a similar good light distribution.

Stimulated by earlier work of the authors we decided to make a direct comparison of the glare from mercury and sodium installations under modern traffic route lighting conditions. We were particularly interested as, in our recent work on appraisal of street lighting installations,* we have been able to take into account road brightnesses, revealing power and glare effects. For the latter we made use of Hopkinson's work and our appraisals which took no account of spectral distribution effects on glare had been in reasonable agreement with subjective assessments.

This supports the authors' statement that the main factor in the preference for existing sodium over mercury installations, from the point of view of glare, is the brightness of the lanterns and the light distribution from them. The high brightness smaller mercury lamp has been housed in a smaller lantern, and earlier mercury installations had high intensities near the horizontal.

For our preliminary trials and experiments we have made mercury lamps similar in dimensions, light output and brightness to the 140-watt sodium lamp and capable of being fitted inside the vacuum flask. The light output, light distribution and flashed area of the lantern is consequently the same for both sources. The trial was carried out using a medium angle beam distribution.

We formed one or two impressions upon which I would like the authors' opinions. Firstly, there was a slight preference for the sodium lantern from the point of view of glare, but the preference was very slight. Secondly, if one stood in the sodium installation for more than a quarter of an hour then a mercury lantern appeared considerably more bright and more glaring. If one stood in the mercury installation for the same time there was less increase in the apparent brightness of a sodium lantern. This recalls a fact we noticed in the early days that, after being in sodium installations for a long time, the adaptation of the eye seems to work in such a way that the blue colour sense is less fatigued so that the side lamps of a car or a cycle headlamp appeared very bright. Have the authors noticed this during their experiments? Thirdly, there appeared to be slightly greater clarity on the part of the road under sodium lamps. We attributed this to a simplified brightness contrast pattern on the road, due partly to the fact that our street had a verge with new green foliage and fresh grass. Fourthly, did the authors during their experiments notice any difference in the colour of the head of the T light patch and its tail. We have noticed this with mercury installations with a coloured road surface; in the nearly monochromatic sodium installations the slight colour difference disappears.

MR. T. L. ROBINSON: I do appreciate the great work that has been put into the tests that have formed the basis of this paper, but I would like to ask whether these tests are taken with dry surfaces and with wet surfaces? Also, has any work been done on the colour-corrected mercury? I found with one scheme, half of it using what we may term the raw mercury, the other half using colour-corrected, the latter with the same colour rating gives a much greater revealing power. I would like the authors' opinion on that, whether they have taken any tests, and, if they have not, I would very humbly suggest it would be a most useful field of investigation.

MR. F. H. PULVERMACHER: It seems to me that the authors have been literally waving a red flag in front of a bull this morning, and it has directed my thoughts to

* Street Lighting Performance, by Ruff and Lambert, Proceedings of the Automobile Division, Institution of Mechanical Engineers, 1954/55, No. 3.

the reason why the bull reacts to a red rag and not to one of another colour. It would seem that the redness of the rag acts as an irritant, indicating that there is a psychological factor which the authors have not dealt with. Similarly the green-blue light of a mercury vapour lamp may have an irritating effect on the observer whilst the yellow of sodium has possibly a soothing action. This is in contradiction to what one would expect since, in nature, green fields and blue skies breed a sense of peace and restfulness, whereas yellow and black are arresting and more conducive of irritation and alarm, particularly when exemplified by signs indicating temper-trying diversions, or the militant wasp. The reason for this seeming paradox may be that with a primary source of light the blue-green end of the spectrum induces irritation, whereas with a secondary source—our fields and skies—the reverse is the case, and what was an irritating positive quantity now becomes a soothing negative. I feel that if the authors could extend their investigations into other monochromatic parts of the visible spectrum, much valuable information would result, and it is my hope that they will continue their researches in this field.

With regard to the choice of light sources for street lighting installations, there is another factor besides colour to be considered, that of economics. It is a fact that we get more light for our money with the sodium lamp than with the mercury vapour lamp.

MR. A. GREENAWAY BROWN: I wish to congratulate the authors on a very excellent and valuable piece of research, and to ask them one question, and urge them to carry on with their research.

The question is, what about the glare from the fluorescent lamp street-lighting lanterns which are now coming to be used more and more? I expect they will say they have not investigated this yet, but it would be very nice to have an opinion from them as to what they think of the glare from these lanterns.

I would like to urge them to carry on with their researches and help us more in finding how to provide good visibility in our streets at night.

MR. J. G. HOLMES: Although the discussion has been primarily concerned with street lighting, this is in fact only one aspect of the greater and more fundamental problems suggested by the title of this paper, and I hope that the important nature of the work will not be lost in consideration of the particular aspect which first suggested this research.

The authors have shown that at high luminance levels a yellow light appears less bright and less glaring than a white light of the same luminance, and that a bluish light appears brighter and more glaring than the white light. It is therefore implied that a light of longer dominant wave-length would have lower luminosity or subjective brightness than a light of shorter dominant wave-length, both of the same luminance or photometric brightness. This would be consistent with the known phenomenon that a very bright red light tends to look orange in colour, that a very bright orange light tends to look yellow and that a very bright white light tends to look bluish. On the other hand it is also well known that a bright red light generally appears brighter than would be expected from simple photometric considerations and, for example, a high intensity beam with a red glass of 10 per cent. transmission appears much brighter than the same beam reduced by a 10 per cent. neutral filter glass. This latter phenomenon might be explained by the chromatic component of the red light which makes it brighter than an achromatic light of the same luminance.

There is a contradiction in these various phenomena, and moreover there is no comprehensive explanation of any of these visual effects at high luminance levels, and

I hope the authors' researches may either be continued or may stimulate others to work on the same problem.

MR. H. E. G. WATTS: The investigation carried out and reported in the paper is a welcome move in the constant endeavour to assess the merits of various types of street lighting, but I suggest that the conclusions could quite easily be misinterpreted if taken out of context, since they are conclusions only from the particular experiment, and it is my belief that there are many other factors which should be considered.

Paragraph 4 of the conclusions suggests reasons for a "layman" expressing a preference for sodium street lighting. I suggest that the preference may very well be due to the preponderance of good sodium street lighting, whereas a high proportion of existing mercury, particularly pre-war installations, suffers seriously from excessive glare, and I suggest that this type of judgment is probably based on the relief of the motorist in getting into some sort of street lighting which is reasonably comfortable for driving.

It seems a pity that the authors did not include fluorescent units in their investigations, particularly in view of the figures given by Professor L. Schneider in his paper, and also other information regarding the great progress of fluorescent street lighting in other countries.

MR. J. M. WALDRAM: This is a piece of work which, naturally, I have discussed with the authors at some length, and I think we have still to discover exactly what these results signify, for it is easy to misinterpret them.

We are dealing here with another subjective phenomenon: glare cannot be measured quantitatively and we do not know how glaring sources are to anybody. I happen to be one of those who can see very little difference between sodium and mercury glare, and it is almost impossible for me to understand that there may be some people to whom one looks very distinctly more bright or glaring than the other. But nobody can discover by how much; all we can do is put up some kind of comparison by which one observer may say, "To me, A looks brighter than B," but nobody knows how bright they are, and it would be quite a mistake to say that, because you have to reduce the brightness of one of them to one-third to eliminate the difference, therefore that source is three times as glaring. That is surely not correct, and I think we ought to sound that note of warning. That agrees with one of the points Mr. Watts may have had in mind.

I think we have two clues as to how big this difference may be. In nearly all subjective work of this kind, if you vary one of the parameters and take the number of people who can detect it, the proportion of observers is at first very small and increases progressively till quite a lot can see it, and then as the parameter is further increased eventually everybody can see it. The curve relating the parameter to the number who can detect it is S-shaped. In this experiment even in the worst conditions the authors measured there were still 10 per cent. of people who were either uncertain or whose judgment went the other way. It is clear we have not yet reached the point when everybody always sees this thing, and if that is so the likelihood is that the difference in the glare sensations is not very great.

If I may take an analogy, when Mr. Stevens and Mr. Ferguson were on the stage I think you had no difficulty in deciding that Mr. Ferguson is taller than Mr. Stevens: the result of an inquiry would be unanimous. But if you take Mr. Stevens and me it is rather more difficult to decide. Perhaps you could if we stood back to back, but when Mr. Stevens is up on the stage and I am down here, you probably cannot tell which is the taller. That difference is on the limit of what one can readily appreciate. I think the kind of phenomenon we are dealing with is something of that sort;

that the amount of the difference is not far from the limit at which you can tell whether one is more glaring than the other and the fact that not everybody can see the difference may be an indication that probably the difference is not very big.

The other thing I think very interesting is the size of the change you have to make in the more glaring source in order to bring about equality. You have to reduce it by one-third, and that seems astonishing. The only conclusion I can draw from that is that the glaring effect is, in fact, not very critically dependent on intensity, because if it were, the change you would have to make would be very much less.

There are two other points we ought to bear in mind in considering judgment on streets and preferences. The first is that one's judgment in such matters always tends to have a bias. Once one conceives the idea that (for example) sodium is better than mercury, every time you see a good sodium installation, you say, "There, what did I tell you?" and register another mental vote for sodium, but when we see a mercury installation which is better than sodium we register nothing at all. The second point is that it is difficult to avoid attributing any virtues of an installation either to the most obvious thing about it or to the feature we are most interested in, which is often its colour. When we see a good one we say, "There; there is another of those good sodium installations." Its excellence may be due to the road surface or to buildings at the side but it all goes down to the credit of sodium. These are some factors that make it very difficult to interpret an undoubted preference that most people have for sodium lighting.

MR. G. C. SMALL (written contribution): Mr. Ferguson suggested that a possible reason for the popularity of sodium was that many of the installations were placed in commission in the post-war period, whereas in the case of mercury the majority was pre-war. Whilst that may be true there have been a large number of mercury installations brought into commission in the last few years—I can think of some towns where this light source is used exclusively—but an even greater number of sodium installations.

It might interest the authors to know that over an area of 6,000 square miles with which I am familiar the number of new sodium lamps installed in the last 12 months is between three and four times that of mercury, and this follows very closely the poll taken during the session this morning. Have the authors any information as to what the present tendency is in the country as a whole and do they feel that, as a result of the recent reduction in the price of sodium lamps, there will be a tendency for this type to be even more widely used in the future when improved lighting schemes are being installed?

THE AUTHORS (in reply): In opening the discussion Mr. Christie made a number of very pertinent remarks. We would agree that the number of observers was too small to establish really authentic answers, and to some extent the work done was only in the nature of a pilot experiment. However, it seems unlikely that any larger number of observers would show a violent general difference from the results so far obtained, although doubtless the more the observers the greater would be the spread of results. Unfortunately this type of experiment is very costly because, as Mr. Waldram has pointed out, these are subjective studies which are extremely difficult to conduct. The observers chosen were such that we hoped to get reasonable and intelligent responses, but, of course, it is difficult to avoid prejudice and pre-knowledge, which tend to invalidate the results.

Mr. Christie's comments on recent experiments on the reflection of light from the road surface are very interesting. It does not seem unreasonable to suppose that the colour of light may react with the road surface, and that the surface should, therefore,

be chosen for colour as well as light distribution. This is one more facet of the old dictum that street surfaces and street lighting must go hand in hand.

Mr. Ruff observed that light distribution is the major factor in street lighting, and this is probably true. In the pilot experiment conducted immediately before this paper was read, the members of the audience indicated that 76 per cent. of them preferred sodium street lighting, and 84 per cent. of them thought mercury street lighting more glaring, as exemplified by current practice. If the questions had asked the audience to confine its views to cut-off lighting the preference might have been very different.

In our experiments we have not observed any changes in apparent brightness with adaptation such as Mr. Ruff reported, and we have not noticed any differences in the head and the tail of the T-shaped patch. Also, we are unable to comment on the effect of trees, since there were none in the road in which our experiments were made.

Mr. Robinson asked whether our tests were made with dry or with wet surfaces. Unfortunately we had to make our street observations in the worst of the winter weather when the street surface varied from damp to very wet. We have, therefore, insufficient evidence to distinguish between the various stages of wetness of the surfaces.

We have no information on colour corrected mercury, nor, in reply to Mr. Greenaway Brown, on the fluorescent tubular lamp. One may guess these two to fall somewhere between tungsten and mercury, but it might be unwise to stake too much on such a guess.

Mr. Holmes returned to what is perhaps the most interesting part of the whole investigation, namely, the basic behaviour of the eyes. We would agree that it is not easy to explain our results in terms of previously observed phenomena. On the other hand, so little has been established about visual behaviour at high levels of luminance that perhaps we should not be surprised at any results. We can but hope, with Mr. Holmes, that these investigations will trigger off other research in these less understood regions.

Mr. Waldram rightly issues a note of warning in the interpretation of the results. Not only must we, as he says, not conclude that because you have to reduce the brightness of one source to one-third to eliminate the difference, therefore that source is three times as glaring, but also we must be very careful in making use of such results outside the context in which they were established. As far as the laboratory work is concerned, clearly such factors as the angle subtended at the eye by the sources, the duration of exposure to the light, the level of luminance and the spectral distribution of the lights is vital. Nevertheless, it is a fact that there is a strongly expressed preference for sodium street lighting, and that both laboratory and street experiments show that substantial changes in source luminance were required in order to elicit equal preference from our observers. Just how big the difference in glare between these different sources is must, of course, depend on the scale by which "bigness" is measured, the method of measurement and doubtless many other factors. But there is no doubt that in laboratory measurements substantial changes in luminance were required to give equal impressions of glare to a number of observers. There is no doubt that in the street there is a substantial majority of people who think mercury more glaring than sodium. The fact, however, that in the controlled experiments this majority appears to be smaller than is given by casual inspection inevitably suggests that there are other factors at work, and it may well be that the prejudice and memory effects mentioned by Mr. Waldram are playing a large part.

Mr. Small inquires whether the present national tendency is to install sodium rather than mercury lighting: there seems no doubt that rather more sodium lighting is being installed at the present time than mercury. It would be unwise to predict whether this trend will continue. The development of mercury discharge lamps still offers many greater possibilities than sodium, particularly in the possibility of getting

much improved colour. Such developments taken together with improvements in light distribution, which may well be possible, might easily reverse the present trend.

Many contributors to the discussion emphasised the desirability of continuing with this and similar research. We would entirely agree that this is not only desirable, but essential, if street lighting is to continue its remarkable course of improvement. Unfortunately, such research is very costly and it is difficult to see how it can continue to be undertaken on the necessary scale, at any rate by commercial research laboratories, if the present tendency to purchase only the cheapest equipment is not modified. We have reached the stage at which more or less satisfactory street lighting can now be provided by relatively simple means, but there is great scope for improvement. If, however, consumers still only purchase the very cheapest equipment which is of "just adequate" performance, there is neither encouragement nor margin for the producer to improve his products.

Fellowship

The Council has accepted the following applications for Fellowship of the Society:—

Mr. D. W. Durrant
Mr. J. S. McCulloch

Register of Lighting Engineers

The Council has accepted the following applications for inclusion on the Register of Lighting Engineers:—

Mr. B. Clarke
Mr. H. Laycock
Mr. G. J. Peat
Mr. J. F. Pickup

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Printed by
ARGUS PRESS, LTD.,
Temple-avenue and
Tudor-street,
London, E.C.4,
England.